AD-A095 644 NAVAL RESEARCH LAB WASHINGTON DC F/G 8/10

A LOOK AT REMOTE SENSING OF THE OCEAN TEMPERATURE STRUCTURE.(U)

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL Memorandum Report 4461	2. GOVT ACCESSION NO.: AD-A095 644
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): A LOOK AT REMOTE SENSING OF THE OCEAN TEMPERATURE STRUCTURE	5. TYPE OF REPORT & PERIOD COVERED: Interim report on a continuing NRL problem.
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): K. D. Flowers	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, DC 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61153N; RR011-08-43; 81-0383-0-0
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Washington, DC 22217	12. REPORT DATE: March 6, 1981
	13. NUMBER OF PAGES: 21
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ocean environment
Acoustic measurement
Climate
Geometric dispersion

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The problem of remotely sensing the ocean temperature structure using acoustic signalling techniques is examined. Specific attention is given to the use of geometric dispersion in determining the modal construction of the acoustic field. This analysis results in plots of modal intensity vs. time and frequency. It is shown that, except in some specific simple cases, the large number of modes present and their close spacing in these dispersion plots require a resolution which is unattainable at this time. However groups of modes of relatively high intensity form patterns in these dispersion plots and should be resolvable. A straightforward comparison of measurements and theory should provide a method of remotely sensing the ocean temperature structure. This method requires experimental verification.

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S/N 0102-LF-014-6601

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A LOOK AT REMOTE SENSING OF THE OCEAN TEMPERATURE STRUCTURE

I. INTRODUCTION

The ocean temperature structure and its temporal variations have a direct effect on our climate and, specifically for the Navy, on our underwater acoustic detection capability. Although there exist direct methods for measuring the ocean temperature structure their use for continuous monitoring on a global scale may be prohibitively expensive. Hence we search for a more economical indirect or remote method. An obvious choice would be to use a satellite to remotely sense the ocean surface temperature. However, the temperature structure as a function of depth is also required and it has been shown[1] that surface temperature is not necessarily indicative of the sub-surface temperature structure. Considering the propagation chracteristics of the ocean one is led to investigate the use of acoustic signals from which the needed information can be determined.

Acoustics has long been used in remote sensing as exemplified by active target detection, sea surface and bottom profiling, and seismic profiling. These uses depend on reflections at impedance discontinuities. More recently, characteristics of acoustic signals transmitted through the medium have been used in medical tomography[2] and in seismic mapping of the earth's interior[3]. It is the techniques employed in these latter areas which may prove applicable to remote sensing of the ocean temperature structure.

Manuscript submitted December 29, 1980.

Part II of this paper is an overview of the problem and sets bounds on important problem parameters.

Part III is a review of the possible acoustic observables and methods of observation and identifies the most promising from a physical, practical, and economical point of view. In Part IV geometric dispersion curves are examined in some detail for a specific type of sound speed profile and Part V contains the summary and conclusions.

II. THE PROBLEM

The problem is to determine the large scale changes in the ocean temperature structure by observing the variations in the acoustic signal field. Assuming that this is possible the average vertical sound speed profile (which can be related to temperature) over the propagation path may be determined using a single source and receiver. To determine horizontal variations one must deploy multiple sources and receivers around the ocean basin to be monitored and combine the observations in a method similar to that used in medical tomography.[2] This paper will consider only the determination of the average vertical profile over the propagation path between a single source and receiver. The solution to the complete problem is seen at this time as being extremely complicated and, if tractable, will probably require an analysis which incorporates additional environmental measurements.

In general the propagation of acoustic signals in the ocean is limited to relatively short ranges. There are two major effects which limit the range - one is absorption loss and the other is boundary interaction loss. However, in deep water by proper choice of source-receiver geometry and frequency it is possible to transmit information over long ranges. By selecting source and

receiver depths the major long range propagation paths, refracted-surface reflected (RSR) and refracted-refracted (RR), both of which avoid bottom interactions are emphasized. By lowering the frequency we reduce the effects of volume inhomogeneities, absorption, surface roughness, and the effects of small scale volume and surface motions.

Although this analysis is restricted to a single-source-receiver geometry one cannot ignore the fact that significant variations in the temperature structure may occur over the path. A significant variation may redistribute the acoustic field such that the received acoustic field is not indicative of the major portion of the path. Hence some knowledge about the environment along the path must be known and taken into account. A glance at available ray diagrams for RR and RSR paths show quite clearly that large areas in range and depth are not sampled with any significant ray. From these diagrams it is estimated that the resolution in range is the order of 100 km. for a fixed single source, single receiver geometry. In addition the number of independent measures obtainable from the received signal is relatively small (<10) from which an estimate of the resolution in depth is of the order of 100 m. For long ranges (3000-4000 km) frequencies will be limited to about 100 Hz and below.

Additional information that is available and needs to be factored into the models includes: 1) the knowledge that the temperature structure below a given depth is stable, 2) the surface temperature that is available from satellite sensors, 3) continuing spot measurements (XBTs), 4) historical data, and 5) known physical features of the ocean (e.g. currents).

III. METHODS

It will be assumed that both source and receiver are fixed relative to the medium. If they are not fixed the assumption will be that their locations are known accurately as a function of time.

An acoustic signal transmitted to long ranges in the ocean has characteristics which are affected by the temperature structure of the medium. These include: 1) amplitude, 2) phase, 3) frequency, 4) arrival time, and 5) a vertical arrival angle, or 6) an equivalent set of modes. Temporal variations of the medium cause all of these characteristics to vary with time. At low frequencies the Doppler shifts caused by medium motions are negligible and the arrival times, arrival angles, or modal structure are slowly varying in time. The amplitude and phase vary slowly or rapidly depending respectively on whether the receiver is in the vicinity of a constructive or destructive interference of the acoustic field. This spatial dependence of the amplitude and phase of the acoustic signal does not allow one to infer, directly, the variations of the medium from a finite number of spot measurements. Hence one is forced to make additional assumptions about the structure of the acoustic field. For example, its representation as a finite set of arrivals or modes which would be fitted to the observations.

The problem then reduces to: 1) selecting a parameterization of the acoustic field, 2) determining the best method of obtaining the required coefficients, and 3) determining the model which relates the observed acoustic field to the environmental (temperature) structure of the medium. Possible approaches are:

A. Modeling the acoustic field as a finite set of ray arrivals

This method is analyzed in detail in Ref. 4. An arrival time (or

change in arrival time) is related to a ray which has a specified trajectory through the medium. The medium is gridded into regions of constant (unknown) sound speed ($\propto$ temperature) and the ray arrival time is represented as a sum of travel times through individual regions. Independent ray arrivals then provide a set of linear equations which may be inverted to provide an estimate of the unknown sound speed in each region sampled by the rays.

The arrival times (or changes in arrival times) may be determined by transmitting complex signals and using correlation techniques at the receiver.

Advantages of the ray method are its simplicity 1) in concept, 2) in relating observations back to medium parameters, and 3) in its source and receiver requirements. Some disadvantages are 1) that the linear equations are nearly singular presenting stability difficulties and 2) that ray representations are limited to higher frequencies thus limiting the range of observation.

B. Modeling the acoustic field as a finite set of modes

Included under this method are the representation of the pressure field p as a set of depth dependent modes $Z_m(z)$ or as a set of radial harmonics $e^{ik_m r}$. That is,

$$p(z) = \sum_m A_m(t)Z_m(z) \quad , \text{ range} = \text{constant},$$

$$\text{or} \quad p(r) = \sum_m B_m(t)e^{ik_m r} \quad , \text{ depth} = \text{constant}.$$

Obviously, using a CW source, both representations require large receiving arrays to determine the individual components. The author is not aware of a direct relation between the component variations and

changes in the medium. However, one possible method would be a direct iterative computation with a comparison of the computed to the observed modal structure. Iteration would proceed until an acceptable match occurred.

The requirement for several large receiving arrays when the problem is extended to ocean basins would probably make this approach economically infeasible. The long and tedious calculations required are not considered excessive because of the relatively slow variations that are expected to be tracked (periods of the order of a week).

This method is considered at this time to be a reasonable scientific approach but not an economically practical one, hence it will not be considered further in this paper.

C. Analysis of dispersion curves

In method A, where the arrival times of different ray trajectories are measured, one may also perform a spectral analysis on the separate arrivals. A plot of the results, i.e. intensity as a function of time and frequency provides information on both arrival times and contributing modes. An analysis of some experimental data explaining major features of the measured intensity vs time and frequency plots is contained in Refs. 5 and 6.

The ability to determine the contributing modes from transient signals is significant because the measuring systems could possibly be reduced to a set of explosive sources and sonobuoy receivers. A distinct advantage of this method is that both ray

arrival times and modes are available which may allow a more accurate determination of the signal field and its relation to the environment. This method is considered in more detail in the following section.

IV. GEOMETRIC DISPERSION

When the acoustic signal is a transient (e.g. a pulse or an explosion) the signal received at great distances in the ocean is a set of individual arrivals spread over several seconds[7]. Each arrival can be associated with a ray path which depends on the sound speed (temperature) structure of the medium. If one also spectrum analyzes the individual arrivals a pattern in time and frequency emerges[5,6]. This pattern is indicative of the modal structure of the acoustic field. The modal field structure in turn depends on the ocean sound speed structure. Examples of these intensity vs time and frequency plots are contained in Refs. 5 and 6 from an experiment in the Mediterranean Sea.

The spreading of energy in time and frequency is a characteristic of a dispersive medium. In this case the dispersion is strictly geometric. Porter[5,6] using the WKB approximation and the stationary phase method, derives the equations necessary to describe the observed dispersion. These consist of equations for the phase integral (Eq. 1), the Bohr-Sommerfeld relation (Eq. 2), the ray cycle length (Eq. 3), the group velocity (Eq. 4), and the relative modal amplitude (Eq. 5).

$$H(\phi, z, z_u) = \frac{\omega}{c_o} \int_z^{z_u} dz \, [N^2(z) - \cos^2\phi]^{1/2} \quad \ldots \qquad (1)$$

$$H(\phi, z_L, z_u) = P_m \quad \ldots \qquad (2)$$

$$S(\phi) = 2 \cos \phi \int_{z_L}^{z_u} dz[N^2(z)-\cos^2\phi]^{-1/2} \quad \ldots \qquad (3)$$

$$U(\phi) = c_o \left[\cos \phi + \frac{2c_o P_m}{\omega S(\phi)} \right] \quad \ldots \qquad (4)$$

$$A_m(z_s,z_R) = \begin{cases} \cos\left[H(\phi,z_s,z_u) - \pi/4\right] \cos\left[H(\phi,z_R,z_u) - \pi/4\right] \\ \quad \text{for } z_L \leq z_s, z_R \leq z_u \\ 0 \quad \text{otherwise} \end{cases} \qquad (5)$$

Note that the WKB approximation, the stationary phase approximation, and the approximation in Eq. (5) are all high frequency approximations. Equation (5) limits the type of refractive profile to those with a single relative minimum. The quantities in Eqs.1 through 5 are:

ϕ = The angle the ray makes with the horizontal at the source

ω = circular frequency,

z_u, z_L = upper and lower ray turning points,

m = mode number,

c_o = reference sound speed,

z_s, z_R = source and receiver depths,

$N(z)$ = $co/c_{(z)}$ = refractive index, and

$$P_m = \begin{cases} (m + 1/2) & \text{for SOFAR (RR) rays} \\ (m + 3/4) & \text{for RSR rays.} \end{cases}$$

The procedure is, for a given refractive profile, to select a mode m and a frequency ω and to compute an angle ϕ from Eq. (2). Alternatively, an easier calculation is to select a mode m and an angle ϕ and to compute ω from Eq. (2). The ray cycle length $s(\phi)$, the group velocity $U(\phi)$, and the relative modal amplitude A_m can then be calculated for each (m, ω, ϕ).

For a given refractive profile the shape of the modal dispersion curves is completely determined. That is, for each m the plot of U vs ω is dependent only on the refractive profile and not on experimental geometry. Examples of these dispersion curves for specific profiles (see Fig. 1) are shown in Figs. 2 and 3 as the solid lines. If one selects the source and receiver depths, then Eq. (5) determines the relative amplitude of the modes. Hence one plots only those modes which have relative intensities (A_m^2) greater than some preselected threshold. Examples of these calculations ($A_m^2 > 0.5$) for specific source and receiver depths are shown as dots in Figs. 2 and 3. If one also selects a horizontal range between the source and receiver, then the U axis can be transformed to a time of arrival axis and a modulation in received level is superimposed along this axis. That is, the phases of the contributing modes coherently add to produce a temporal modulation in the received signal. In terms of rays this implies that signal levels will be high when the range is an integral number of cycle lengths (Eq. 3) and low otherwise.

If the source spectrum is not flat an additional modulation exists along the frequency axis. This modulation, since it weights the levels of individual modes, can alter the temporal arrival structure of the signal.

The solid line in Fig. 1 is a representative profile of the North Atlantic south of Bermuda. The other curves represent an N^2 bi-linear and an N^2 tri-linear fit to this profile. Note that no attempt was made to make these fits "optimum".

For N^2 linear over segments of Z the integrals in Eqs. 1 through 3 can be performed analytically. Calculations were made for N^2 linear over the 2 and 3 segment refractive profiles of Fig. 1. In Fig. 2 is a plot of

the modal dispersion curves (solid lines) for the bi-linear profile out to $U=1493.5$ m/sec., which corresponds to a source angle $\phi=8.17°$. For a few special cases, one of which is the N^2 bi-linear profile, the modal dispersion curves have constant amplitude independent of U, if the source and receiver are both on the axis. Hence those modes plotted in Fig. 2 are for the source and receiver on axis and ${A_m}^2 > 0.5$. If, however, the source and receiver are located at a depth of 950 m (axis is at 1060 m) then those modes such that ${A_m}^2 > 0.5$ are indicated by the dots. Figure 3 is a plot of representative modal dispersion curves for the N^2 tri-linear profile and the dots represent the modes which have ${A_m}^2 > 0.5$ for the source and receiver at 950 m. Note that the minimum sound speed (1492 m/sec) for this refractive profile does not correspond to the slowest arrival (1491.2 m/sec) and that the dispersion curves are double valued (actually triple valued when all frequencies are allowed). This phenomenon, explained elsewhere[8,9] was formerly considered by the author to be relatively rare but this may not be the case. Figure 4 has the same N^2 bi-linear profile as in Fig. 1. With source and receiver on axis those rays which turn over between the surface and a depth of 346 m are plotted. The dots correspond to the profile which is identical to the N^2 bi-linear profile up to a depth of 346 m, where the upper portion is replaced with an N^2 linear segment with surface sound speed of 1527 m/sec (vice 1537 m/sec). This corresponds to a change in surface temperature of 2°C. Only limited amounts of the data were plotted. For those signals arriving slower than (or equal to) 1498 m/sec the dots and solid lines coincide.

Several observations can be made from these calculations. First, the number of modes present is large and the spacing between modes is relatively small. Second, the spectral energy is concentrated in bands in the frequency,

velocity plots. Third, these bands come closer together as U increases. Hence one can see from Fig. 2 that, if resolution is not sufficient to see individual modes in the high intensity band, then an inaccurate depth position could be interpreted as a change in sound speed minimum. Figure 3 indicates that a more complicated profile will introduce more modes and that the slowest group velocity is not necessarily indicative of the minimum sound speed. Figure 4 shows that even for a simple case that determining a substantial change in the profile near the surface will probably not be possible using deep sources and receivers.

This latter observation is important since most variations one would wish to measure occur in this near surface region. Apparently the idea of separating the field into individual modes from measured dispersion curves will probably not be possible, except in very special cases. The fact that the energy arrives in relatively distinct frequency bands indicates another possible approach which is illustrated in Fig. 5. Figure 5 has the same sound speed profiles as Fig. 4. That is, one is trying to obtain a measure of the effect of changing the near surface sound speed structure. The difference between Figs. 4 and 5 is that the source has been moved from the axis to a depth of 346 m. Individual modes have not been plotted but have instead indicated the bands of modes which have a $A_m^2 > 0.5$ for the two cases. In Fig. 5a) the sound speed profile is bi-linear while in Fig. 5b) the sound speed profile has the near surface modification. As can be seen, sufficient difference exist between these two cases so that this should be distinguishable experimentally. Thus, when the experimental geometry is known and controlled, the sound speed structure may be determined by varying the source depth and matching the energy bands with the computed dispersion diagrams.

V. SUMMARY AND CONCLUSIONS

Methods of remotely sensing the ocean temperature structure using acoustic signaling methods have been considered. The idea of parameterizing the field in terms of modes or radial harmonics and tracking the sets of coefficients was rejected because the measuring system would be uneconomical. The method of using ray trajectories and ray arrival times is being pursued by Munk, et al[4] but has the inherent difficulties associated with singular or nearly singular sets of equations. The possibility of using geometric modal dispersion to provide information on both modal content as well as arrival times was considered in more detail. A few calculations showed that, in general, the number of modes present, the separation of the modes, and the combined effects of source-receiver depths and refractive profile complexity require the measurement system to have a degree of resolution which is probably unobtainable. This is not to say that the method cannot be used in special cases. For example the method has been applied to an Arctic profile[10] quite successfully.

If, however, one relaxes the condition of determining modal structure to that of relating the bands of contributing modes to changes in the medium, then it may be possible to determine the vertical sound speed structure. Determination of the resolution with which this may be accomplished requires further calculation and more importantly a well controlled experiment over significant ranges.

It is concluded then that the use of geometric dispersion to determine individual modes, in most cases, requires the medium to be known in an unreasonable amount of detail. However, by matching high signal level bands on the dispersion plots one may very simply determine the changes in the

vertical sound speed structure. These conclusions are based on a range independent-single vertical slice through the ocean. Generalization to multiple-slice range-dependent conditions introduces further complications.

It is the authors opinion that an experiment (both computer and ocean) needs to be performed to determine if the method of "band matching" is possible. If it is shown to be unacceptable then the use of direct methods of measuring the oceans parameters should be reconsidered.

ACKNOWLEDGMENTS

The author would like to thank Drs. R. M. Fitzgerald and T. C. Yang for many helpful discussions.

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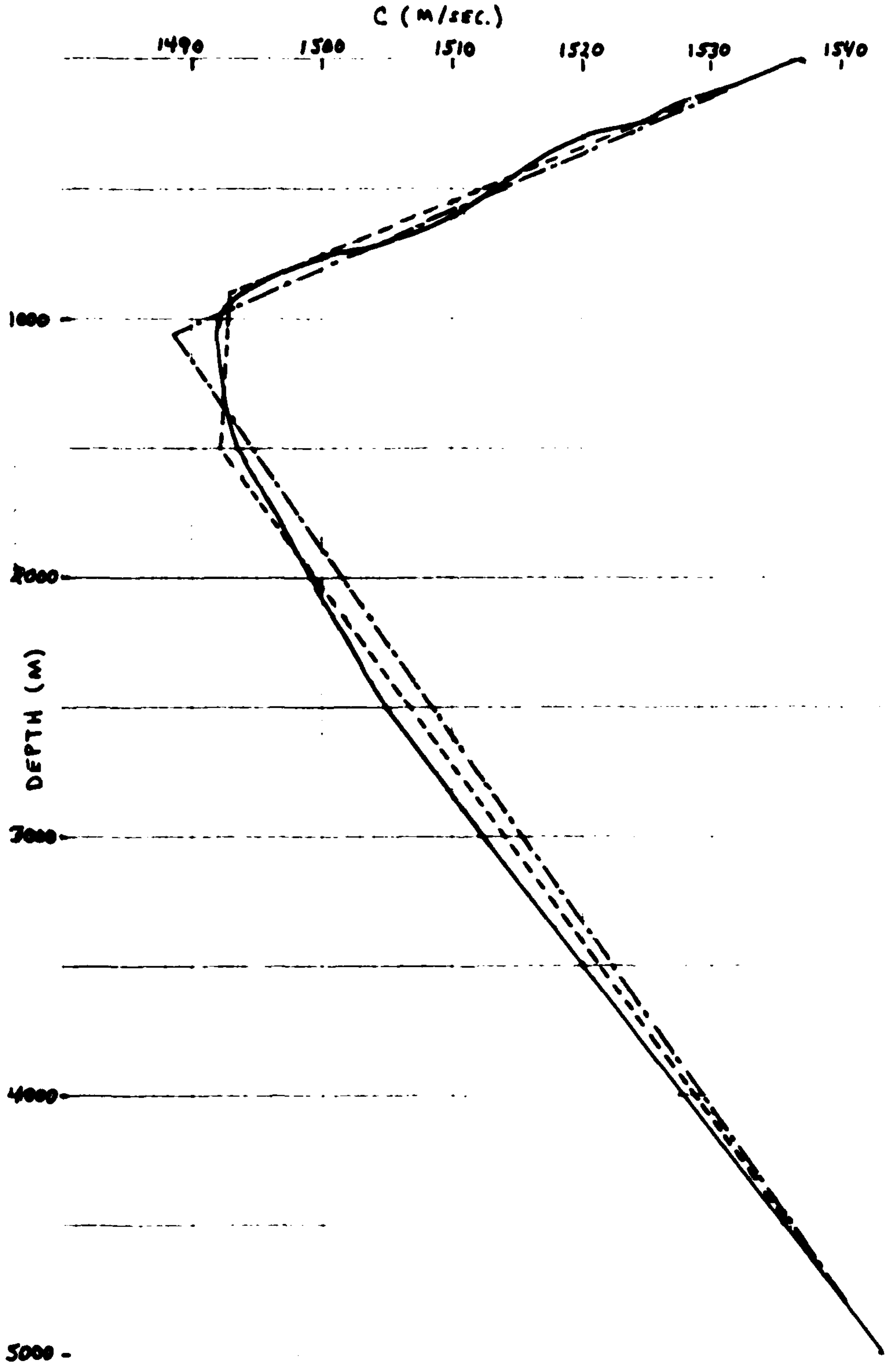

Fig. 1 - Solid line indicates a typical Atlantic profile from south of Bermuda. A bi-linear fit (____ .____) and a tri-linear fit (----) are also indicated.

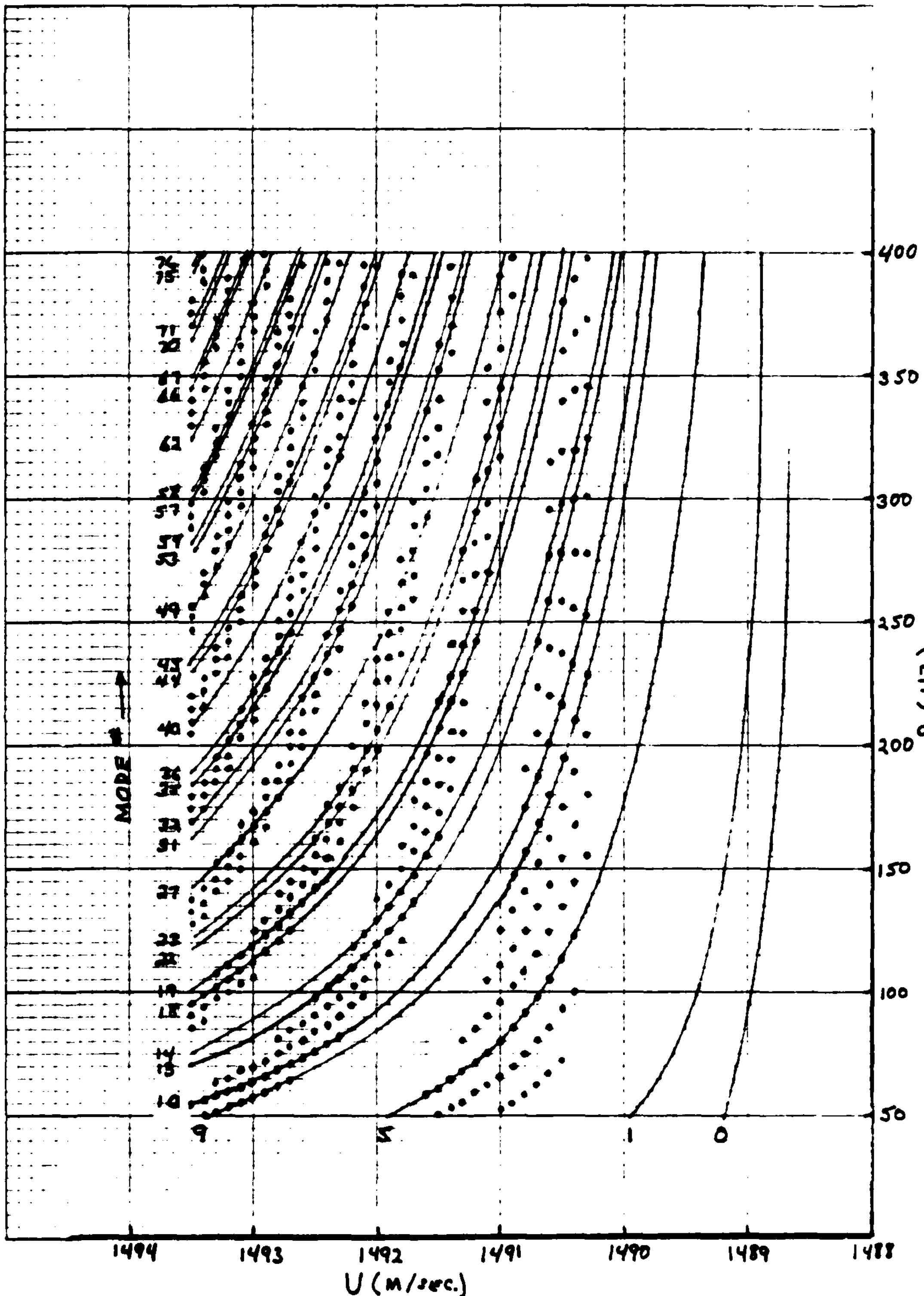

Fig. 2 - Dispersion curves for bi-linear profile of Fig. 1 with $A_m^2 > 0.5$. Solid lines are for source and receiver on sound channel axis (1060 m) and dots are for source and receiver at 940 m.

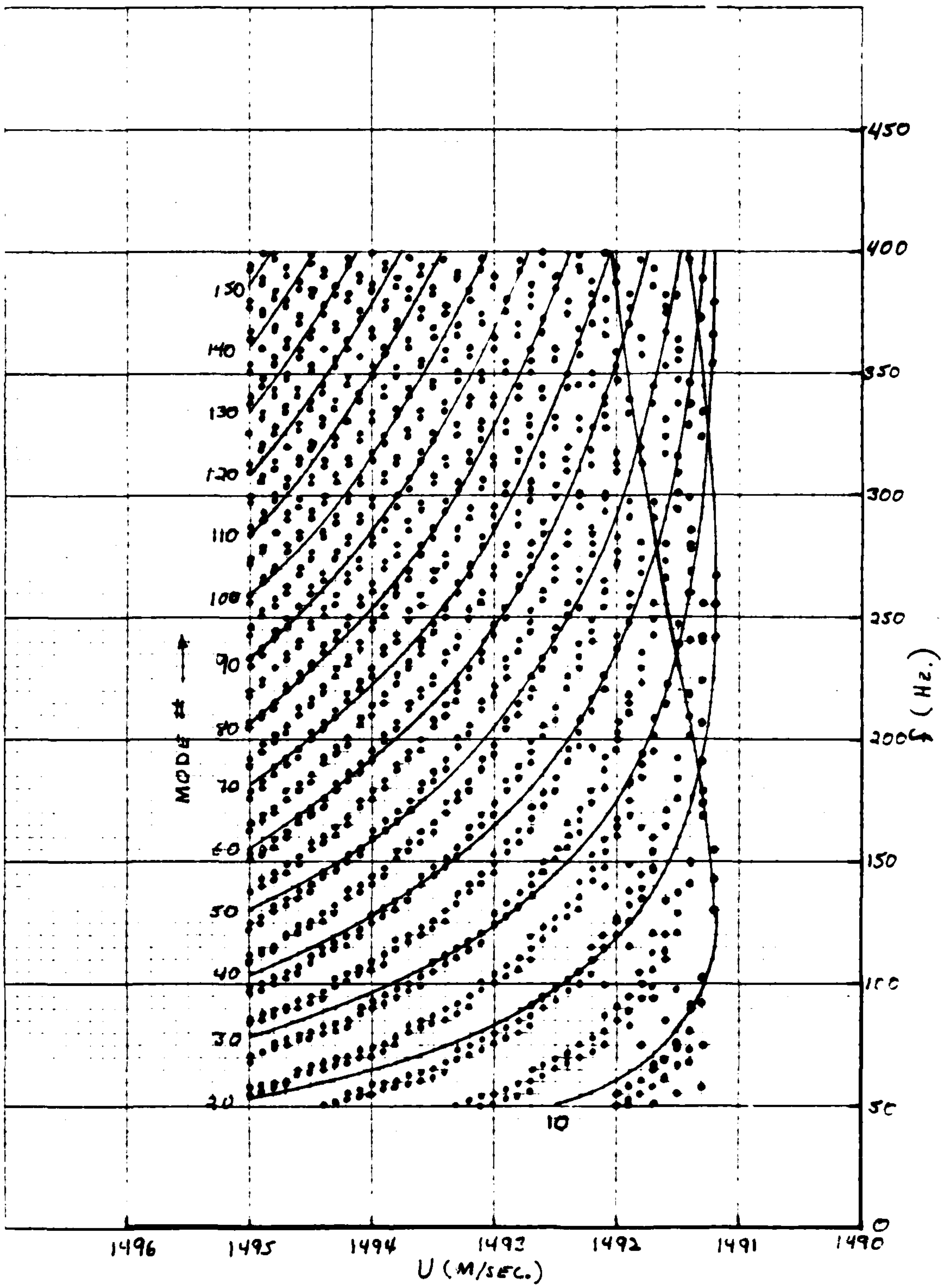

Fig. 3 - Dispersion curves for tri-linear profile of Fig. 1. Solid lines are only representative and dots are for $A_m^2 > 0.5$ with source and receiver at 940 m.

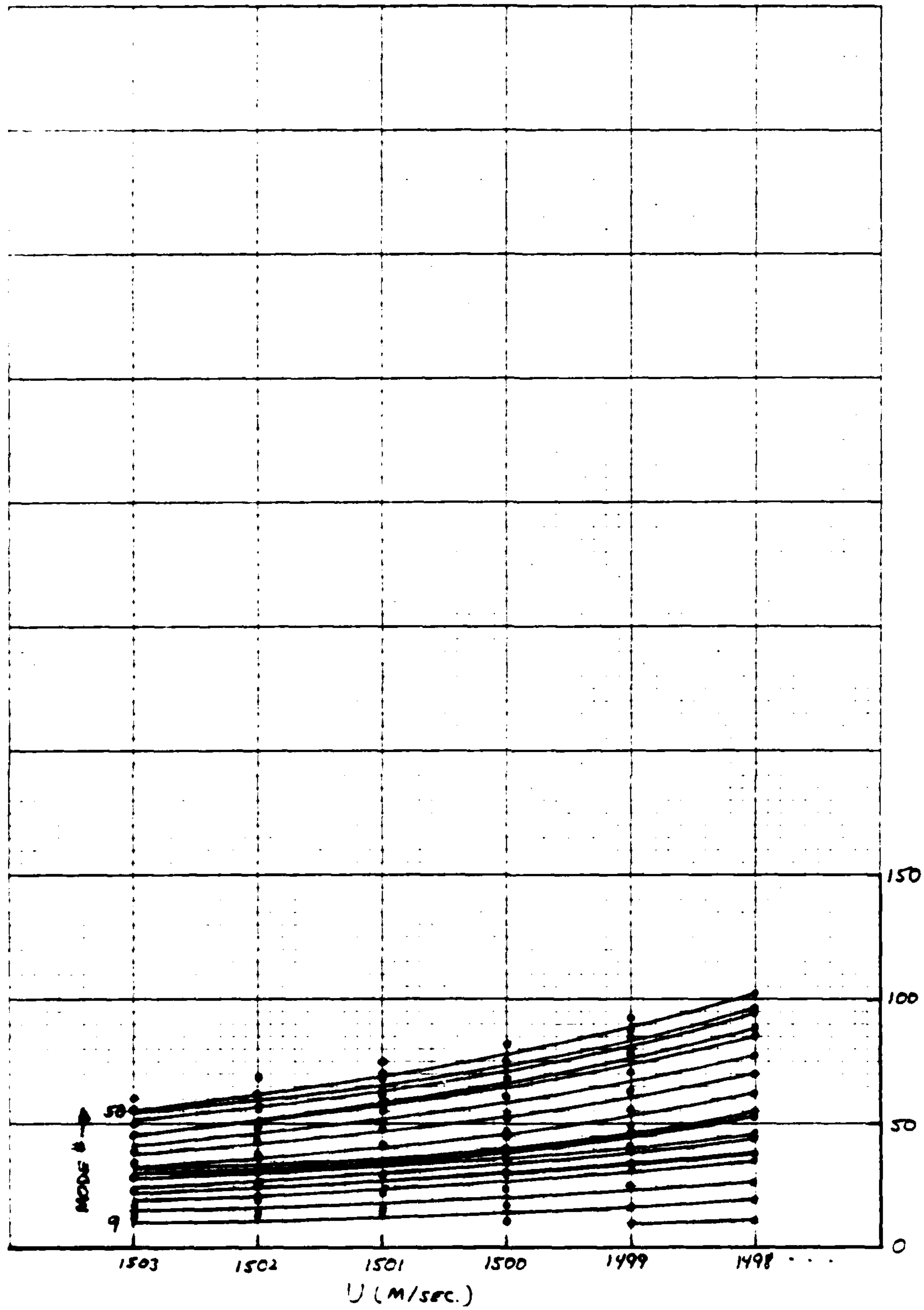

Fig. 4 - Dispersion curves for bi-linear profile of Fig. 1 for rays that turn over between the surface and 346 m. Solid lines are for those modes with $A_m^2 > 0.5$ while the dots are for the same profile except that the upper 346 m. portion is replaced with an N^2 linear segment intercepting the surface at 1527 m/sec (vice 1537 m/sec) corresponding to a 2^{o}C change in surface temperature.

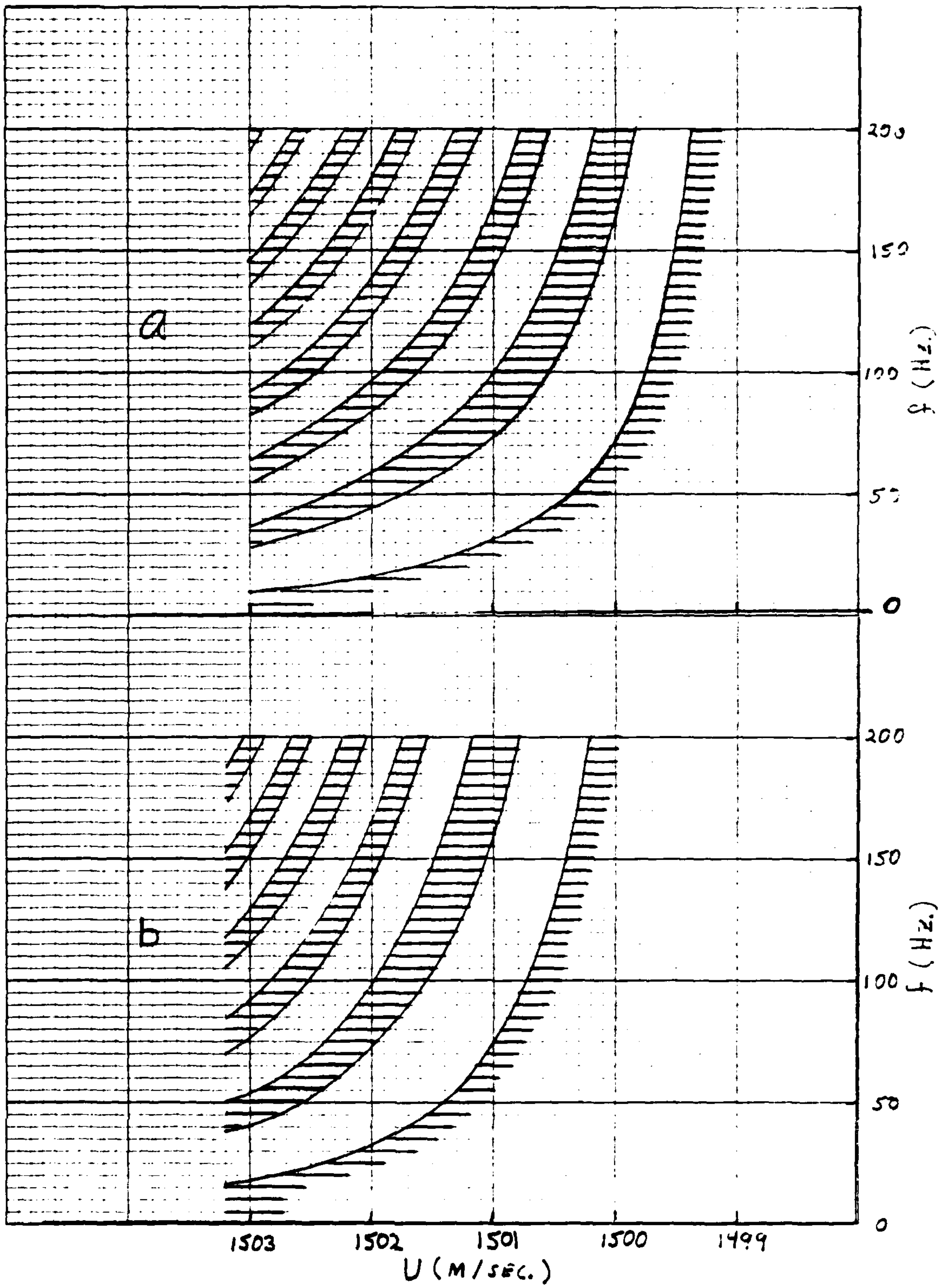

Fig. 5 - Dispersion plots for the profiles used in Fig. 4 where the source is now at 346 m. a) bi-linear profile and b) the near surface modified profile. Hatched areas represent dense regions of modes with $A_m^2 > 0.5$.

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